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Supply Chain Sustainability Analysis of Indirect Liquefaction of Blended Biomass to Produce High Octane Gasoline

Energy Systems Division

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1 INTRODUCTION

The Department of Energy's (DOE) Bioenergy Technologies Office (BETO) aims at developing and deploying technologies to transform renewable biomass resources into commercially viable, high-performance biofuels, bioproducts and biopower through public and private partnerships (DOE, 2015). BETO and its national laboratory teams conduct in-depth techno-economic assessments (TEA) of biomass feedstock supply and logistics, conversion technologies to produce biofuels, and overall system sustainability. A design case is a TEA that outlines a target case for a particular biofuel pathway. It enables preliminary identification of data gaps and research and development needs, and provides goals and targets against which technology progress is assessed.

In addition to developing a TEA, BETO also performs a supply chain sustainability analysis (SCSA). The SCSA takes the life-cycle analysis approach that BETO has been supporting for more than 17 years. It enables BETO to identify energy consumption, environmental, or sustainability issues that may be associated with biofuel production. Approaches to mitigate these issues can then be developed. Additionally, the SCSA allows for comparison of energy and environmental impacts across biofuel pathways in BETO's research and development portfolio.

This report describes the SCSA of the production of renewable high octane gasoline (HOG) via indirect liquefaction (IDL) of lignocellulosic biomass. This SCSA was developed for the 2017 design case for feedstock logistics (INL, 2014) and for the 2022 target case for HOG production via IDL (Tan et al., 2015). The design includes advancements that are likely and targeted to be achieved by 2017 for the feedstock logistics and 2022 for the IDL conversion process. The 2017 design case for feedstock logistics demonstrated a delivered feedstock cost of $80 per dry U.S. short ton by the year 2017 (INL, 2014). The 2022 design case for the conversion process, as modeled in Tan et al. (2015), uses the feedstock 2017 design case blend of biomass feedstocks consisting of pulpwood, wood residue, switchgrass, and construction and demolition waste (C&D) with performance properties consistent with a sole woody feedstock type (e.g., pine or poplar). The HOG SCSA case considers the 2017 feedstock design case (the blend) as well as individual feedstock cases separately as alternative scenarios when the feedstock blend ratio varies as a result of a change in feedstock availability. These scenarios could be viewed as bounding SCSA results because of distinctive requirements for energy and chemical inputs for the production and logistics of different components of the blend feedstocks.

Water resource consumption is intimately connected to sustainable energy production. The SCSA examines the water resource impacts of the HOG production pathway through estimating the water consumption of its full supply chain.

Figure 1 displays the stages in the supply chain that are considered in the SCSA. In this analysis, we consider the upstream impacts of producing each energy and chemical input to the supply chain.

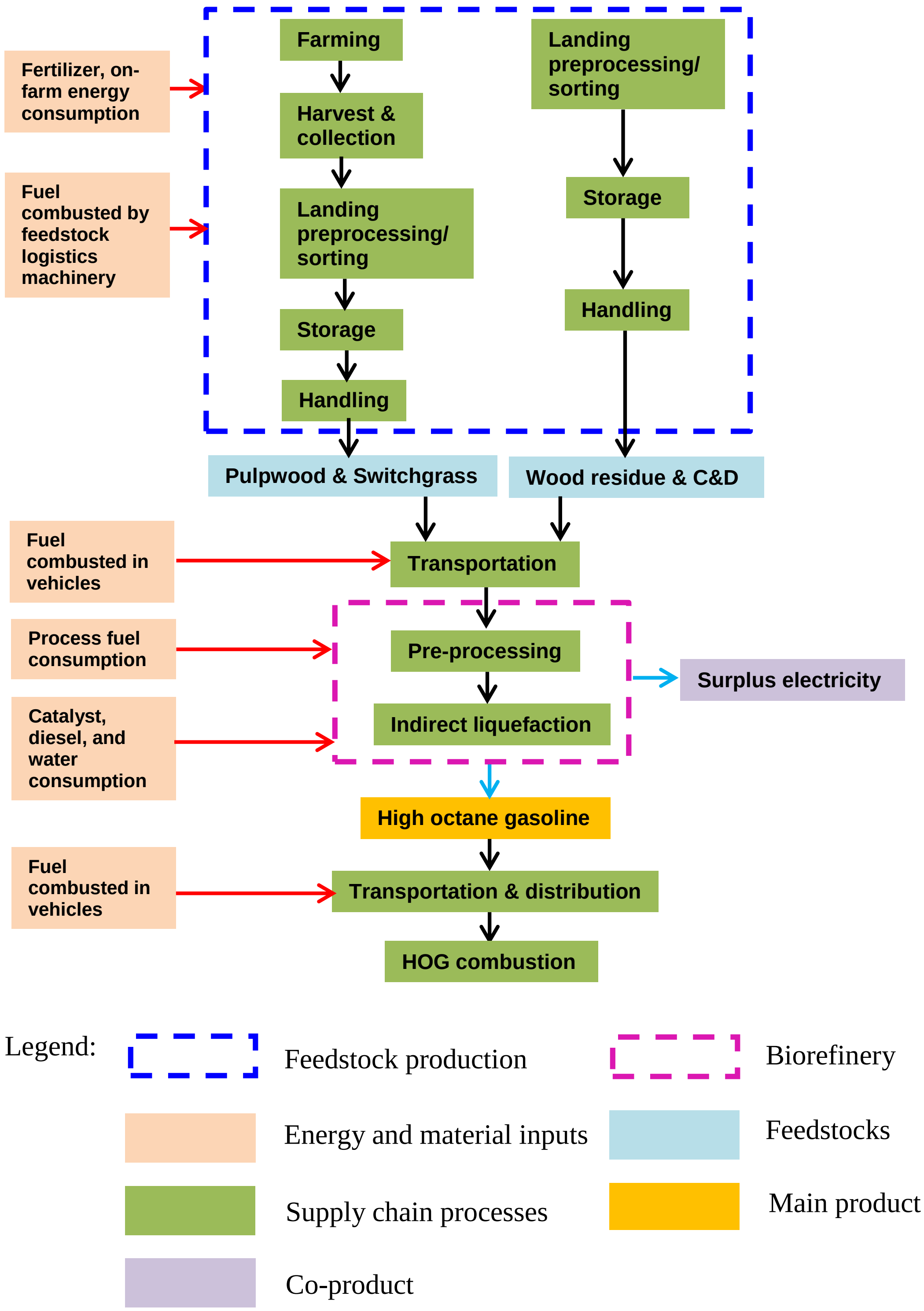


FIGURE 1 General stages considered in the supply chain sustainability analysis

2 METHOD AND DATA

Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET^{TM})[1] model as released in October 2014 was used to produce the SCSA results. The GREET model, developed with the support of DOE, is a publicly available tool for the life-cycle analysis of transportation fuels that permits users to investigate energy and environmental impacts of numerous fuel types and vehicle technologies. GREET computes fossil, petroleum, and total energy use (including renewable energy in biomass), emissions of greenhouse gases (GHG) (CO_2, CH_4, and N_2O), and emissions of six air pollutants: carbon monoxide (CO), volatile organic compounds (VOCs), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter with an aerodynamic diameter below 10 micrometers (PM_{10}) and below 2.5 micrometers ($PM_{2.5}$). This version of GREET has been expanded to include water consumption factors for major fuel and chemical production pathways for estimation of life-cycle water consumption of various fuel production pathways (Lampert et al., 2014; Lampert et al., 2015).

2.1 Material and energy requirement of feedstock production and logistics

INL chose a blended feedstock for the 2017 SOT design case (INL, 2014). The feedstock blend approach takes advantage of low cost resources (i.e., wood residues and C&D waste), while producing a feedstock with a low ash content. The blended feedstock comprises pulpwood (45 wt%), wood residues (32 wt%), switchgrass (3 wt%), and C&D waste (20 wt%).

The total energy requirements for feedstock production for each unit process is summarized in Table 1, with the shares of fuel type presented in Table 2. Note that we assumed that the farming of pulpwood feedstock requires equivalent amount of fertilizers as the farming of poplar does, due to lack of the farming chemical inputs data for pulpwood.

There are seven possible feedstock logistics operations for all feedstocks. Farming, harvesting and collection are considered for the production of switchgrass and pulpwood. Diesel is consumed for these operations. All feedstocks, except switchgrass, consider a landing preprocessing/sorting operation, which consumes mostly diesel for steps including debarking, size reduction, sorting, and screening. Additional energy requirements are met by electricity. Three additional stages (transportation, storage, and handling), which all use diesel fuel, are processes that every feedstock undergoes. Regardless of feedstock, the preprocessing section consumes mostly natural gas for energy, with the additional 5% energy demand met by electricity. Parameters used to determine energy consumed during feedstock transportation are shown in Table 3. Vehicle payloads were adopted from GREET (ANL, 2015), while other parameters, like transportation distance and moisture content, were determined by INL (INL, 2014). These data were incorporated into the new IDL pathway in the GREET model. Data for the last two stages of the supply chain, fuel transportation and distribution and fuel combustion were obtained from GREET.

[1] GREET model and documentation are available at http://greet.es.anl.gov

TABLE 1 Energy consumption for all unit processes for each feedstock and the feedstock blend

	Pulpwood (Btu/dry ton)	Wood Residues (Btu/dry ton)	Switchgrass (Btu/dry ton)	C&D Waste (Btu/dry ton)	Blended Feedstock (Btu/dry ton)
Farming[a]	20,496		56,870		10,929
Harvesting and Collection[b]	182,780		122,850		85,937
Landing Preprocessing/Sorting[b]	231,520	110,250		410,250	221,514
Storage[b]	8,460	8,460	21,830	8,460	8,861
Handling[b]	42,690	42,690	41,900	42,690	42,666
Transportation[b,c]	138,491	138,491	36,354	107,715	129,271
Preprocessing[b]	408,010	408,010	285,830	408,010	404,345

[a] Tan et al., 2015
[b] INL, 2014
[c] ANL, 2015

TABLE 1 Share of fuel type for each feedstock (INL, 2014)

	Pulpwood		Wood Residue		Switchgrass		C&D Waste	
	Share	Fuel Type[a]	Share	Fuel Type[a]	Share	Fuel Type[a]	Share	Fuel Type[a]
Farming	100%	D			100%	D		
Harvesting and Collection	100%	D			100%	D		
Landing Preprocessing/Sorting	87%[b]	D	87%[b]	D			87%[b]	D
	13%	Elec	13%	Elec			13%	Elec
Transportation	100%	D	100%	D	100%	D	100%	D
Preprocessing	95%	NG	95%	NG	95%	NG	95%	NG
	5%	Elec	5%	Elec	5%	Elec	5%	Elec
Storage	100%	D	100%	D	100%	D	100%	D
Handling	100%	D	100%	D	100%	D	100%	D

a. D: diesel, NG: natural gas, Elec: electricity
b. Updated from INL (2014), which used 87% natural gas

TABLE 3 Feedstock transportation parameters

	Transportation Mode[a]	Truck Payload (tons) [a]	Transportation Distance (miles) [b]	Transportation Moisture Content [b]	Moisture Content at Reactor Throat [b]
Pulpwood	Class 8b Heavy Duty Truck	25	50	30%	10%
Wood Residues	Class 8b Heavy Duty Truck	25	50	30%	10%
Switchgrass	Class 8b Heavy Duty Truck	25	15	20%	9%
C&D Waste	Class 8b Heavy Duty Truck	25	50	10%	10%

[a] ANL, 2015
[b] INL, 2014

2.2 Material, energy, and water requirement of indirect liquefaction conversion processes

The 2022 design features a processing capacity of 2,205 U.S. short tons of dry biomass per day and a HOG yield of 64.9 gallons per dry U.S. short ton of feedstock at the biorefinery. At the biorefinery, a small amount of diesel fuel is consumed by diesel trucks carrying the biomass feedstock and a truck dumper that unloads the trucks into a hopper. A heat integration network is designed for heat and power production to lower energy consumption and boost product yields. As a result, the plant realizes energy self-sufficiency by combusting char, fuel gas, an unreformed syngas slipstream, and a portion of unreacted syngas from the methanol synthesis reactor. Using these IDL process-internal energy sources eliminates the need to consume any external energy sources. In addition, a small amount of surplus electricity is produced at the biorefinery and is exported to the grid. A variety of catalysts, e.g., beta zeolite and a tar reformer catalyst, are used for tar reforming processes, methanol synthesis, and the conversion of dimethyl ether (DME) to HOG. Consumptive water is required for cooling of the IDL system and for making up boiler feed water. Table 4 lists the direct material, energy, and water consumption for the modeled IDL conversion process at the plant (Tan et al., 2015).

We use the GREET catalyst module that we have recently developed (Wang et al., 2015) to estimate the emissions and water consumption associated with manufacturing and use of the catalysts required for the IDL process. For this SCSA, we developed new estimates of the energy consumed to produce zinc oxide (ZnO) and magnesium oxide (MgO) (Benavides et al., 2015; Wang et al., 2015). A number of compounds are consumed at low levels in the IDL process that are produced via complex, proprietary processes. These compounds include methyl diethanolamine, dimethyl sulfide, LO-CAT chemicals (chelated iron and caustics), boiler feed water chemicals (sodium sulfite, hydrazine, morpholine, etc.), and cooling tower chemicals (phosphates, azoles, copolymers, zinc). As no publicly-available material and energy flow data for the production of these compounds are available, these compounds have been excluded from the SCSA. We examine the influence of the exclusion of these compounds on supply chain GHG emissions in Section 3.2.

TABLE 4 Key parameters of the indirect liquefaction process

	Value	Unit
Yield of HOG	64.9	gal/dry ton feedstock
Surplus electricity	0.013	kWh/gal of HOG
Diesel energy use	213	Btu/gal of HOG
Char produced and combusted	110,834	Btu/gal of HOG
Fuel gas produced and combusted	110,727	Btu/gal of HOG
Syngas produced and combusted	111,024	Btu/gal of HOG
Magnesium oxide consumption	0.5	g/gal of HOG
Fresh olivine consumption	41.3	g/gal of HOG
Tar reformer catalyst consumption	0.7	g/gal of HOG
Methanol synthesis catalyst consumption	0.4	g/gal of HOG
DME catalyst consumption	0.5	g/gal of HOG
Beta zeolite catalyst consumption	4.8	g/gal of HOG
Zinc oxide catalyst consumption	1.6	g/gal of HOG
Water consumption	1.8	gal/GGE[a] of HOG
HOG properties		
-Lower heating value	111,560	Btu/gallon
-Density	2,655	g/gallon
-Carbon content	83.37	%, by mass

a: Gasoline gallon equivalent

3 RESULTS AND DISCUSSION

3.1 Supply chain GHG emissions

The IDL process produces HOG and a small amount of surplus electricity. We used the energy-based co-product allocation method to allocate the energy, emission, and water burdens between HOG and the surplus electricity. Figure 2 shows the supply chain GHG emissions[2] of the HOG fuel.

[2] GHG emissions are reported as grams carbon dioxide equivalents per mega joule of fuel. Carbon dioxide equivalent emissions include CO_2 emissions and CH_4 and N_2O emissions multiplied by their 100-year global warming potentials according to the Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC)

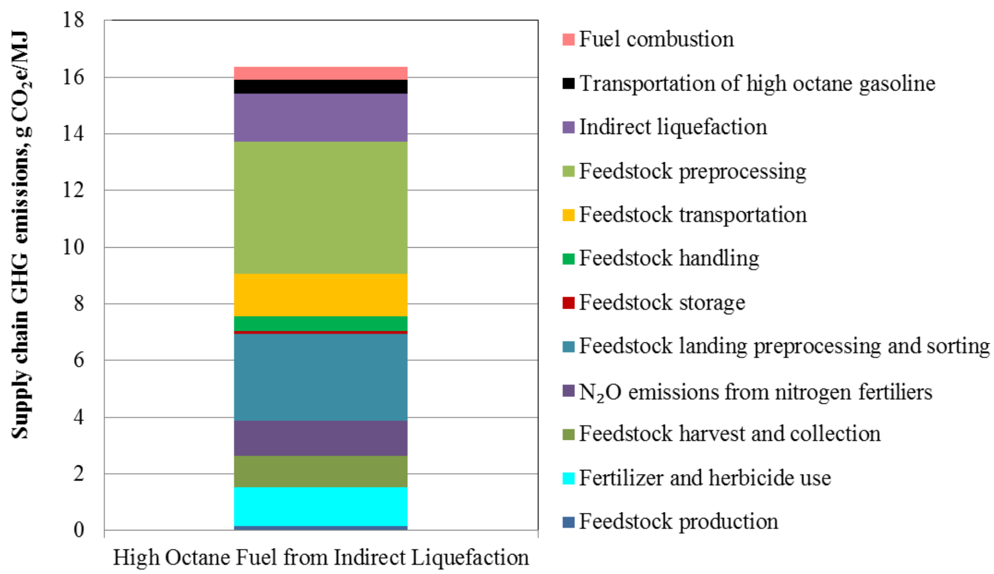


FIGURE 2 Supply chain GHG emissions of HOG produced via the IDL process

The largest contributor (28%) to the supply chain GHG emissions is the feedstock preprocessing, 90% of which are from natural gas consumption. The balance of GHG emissions are from electricity consumption. Therefore, driving down the energy consumption associated with comminution, drying, and densification of the feedstock will be key to reducing the contribution of feedstock preprocessing to supply chain GHG emissions. Feedstock landing preprocessing and sorting, which consumes mostly diesel for feedstock debarking, size reduction, sorting, and screening, contributed to 19% of the supply chain GHG emissions. The IDL conversion process contributes 10% (1.7 g CO_2e/MJ) of the supply chain GHG emissions. The IDL process is almost 100% energy self-sufficient because it taps heat and power produced from the combustion of intermediate biogenic syngas, fuel gas, and char that are produced during the IDL process. With little contribution from energy consumption to GHG emissions from the IDL process, the production and use of catalysts become a significant contributor (61%) to the minimal GHG emissions from this supply chain step. Combustion of the syngas, fuel gas and char would produce CH_4 and N_2O and these emissions are estimated through the application of emission factors in the GREET model developed for boiler combustion of refinery fuel gas and char. Methane and N_2O emissions from combustion of intermediate syngas, fuel gas, and char are responsible for about 29% of IDL GHG emissions. Biomass feedstock transportation contributed 9% of the supply chain GHG emissions, followed by production and use of fertilizers (8%), N_2O emissions from nitrogen fertilizers (8%), feedstock harvest and collection (7%), and feedstock handling (3%).

The supply chain GHG emissions of HOG produced via IDL are about 16.4 g CO_2e/MJ, in comparison to about 93.4 g CO_2e/MJ for gasoline blendstock produced from petroleum crudes. HOG produced via IDL with this feedstock blend therefore offers about an 82.4% GHG reduction as compared to conventional gasoline (Figure 3). The biogenic CO_2 credit from carbon uptake during the growth of biomass feedstocks is the major driver of the GHG emission reduction for HOG, and the feedstock and fuel production phase is also more favorable for HOG than petroleum gasoline blendstock that has significant GHG emission burdens from crude refining and crude recovery. To reiterate, we used the energy allocation co-product handling technique to address co-production of electricity along with HOG. If the system expansion, or displacement, technique were adopted to handle the electricity co-product, the resulting supply-chain GHG emissions drop slightly to 16.3 g CO_2e/MJ (an 82.5% reduction) assuming the electricity displaced has the characteristics of the national average grid mix as delineated in Table 5.

TABLE 5 United States average grid mix (ANL 2015)

	Share of National Grid
Residual Oil	0.45%
Natural Gas	26%
Coal	41%
Nuclear Power	19%
Biomass	0.32%
Hydroelectric	7.0%
Geothermal	0.42%
Wind	5.0%
Solar PV	0.40%
Others	0.41%

Figure 3 contains error bars that show the 10^{th} and 90^{th} percentile values of the net supply chain GHG emissions as determined through stochastic modeling with GREET. We used GREET's stochastic modeling feature to conduct simulations with probability distribution functions for key parameters. It is important to note that point values, rather than probability distribution functions, were used for the parameters in Tables 1 to 4 because there were insufficient data to generate distribution functions. Rather, the GREET stochastic simulations use the probability distribution functions in the model for many other parameters, such as energy consumed during fertilizer production and N_2O emission factors for nitrogen fertilizers.

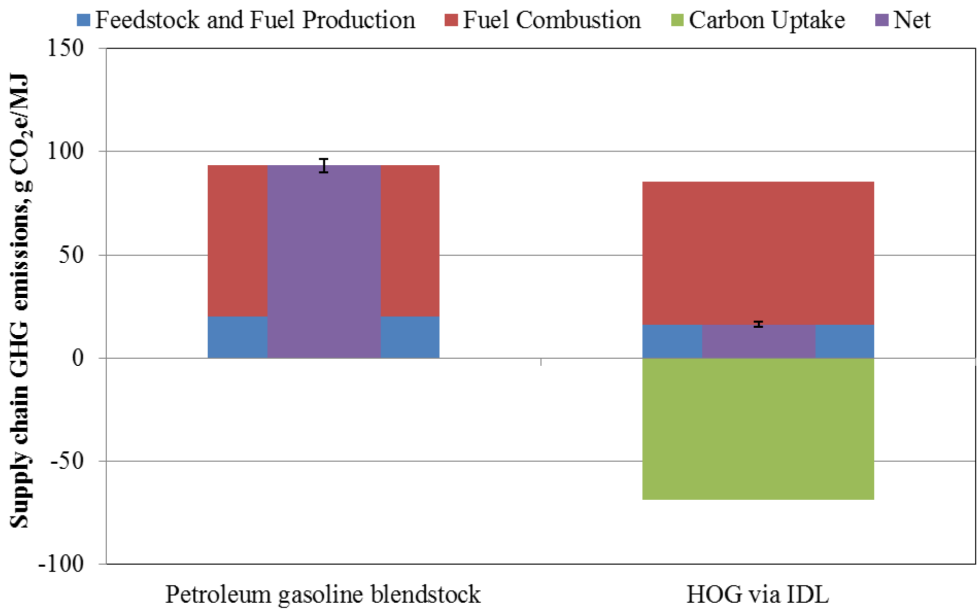


FIGURE 3 Supply chain GHG emissions of HOG produced via IDL, in comparison to petroleum gasoline blendstock

3.2 Supply chain water consumption

Figure 4 shows the supply chain water consumption of HOG via IDL. In this analysis, we define water consumption as the amount of water withdrawn from a freshwater source that is not returned (or returnable) to a freshwater source at the same level of quality. This definition is often used for "blue water" in water footprinting analyses. For the 2022 IDL target design case with the blended feedstocks, the largest contributor (62%) to the supply chain water consumption is the IDL process (i.e., biorefinery), which consumes water for process cooling and boiler feed water makeup. Other steps that consume significant amounts of water in the IDL supply chain include production and use of fertilizers (19%), feedstock landing preprocessing and sorting (8%), and feedstock preprocessing (5%). Water consumption embedded in the production of upstream process energy and chemicals (i.e., indirect water consumption) used at the biorefinery is a minor piece of the whole supply chain water consumption. Therefore, the direct water consumption at the IDL process presents the largest reduction potential for the supply chain water consumption of HOG.

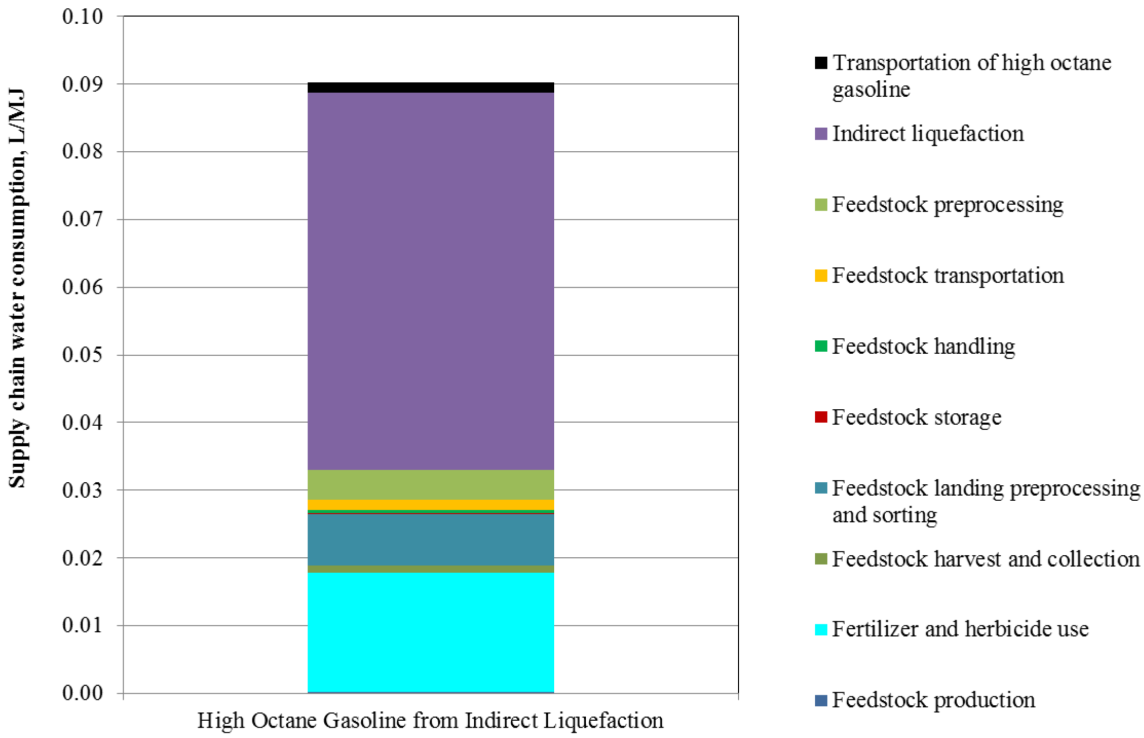


FIGURE 4 Supply chain water consumption of HOG produced via IDL

Figure 5 shows that the supply chain water consumption of HOG produced via IDL is about 0.09 L/MJ, in comparison to about 0.14 L/MJ for petroleum gasoline blendstock. This difference represents approximately 37% less water consumption in the supply chain of HOG than in conventional gasoline's supply chain. The main reason for this benefit is that production of the biomass feedstock for the HOG via IDL pathway is less water-intensive than that of crude oil recovery.

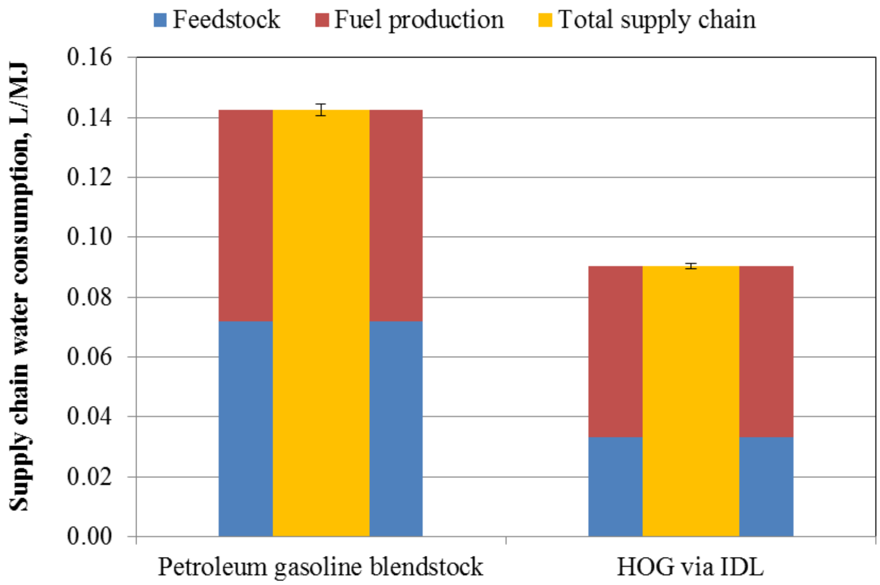


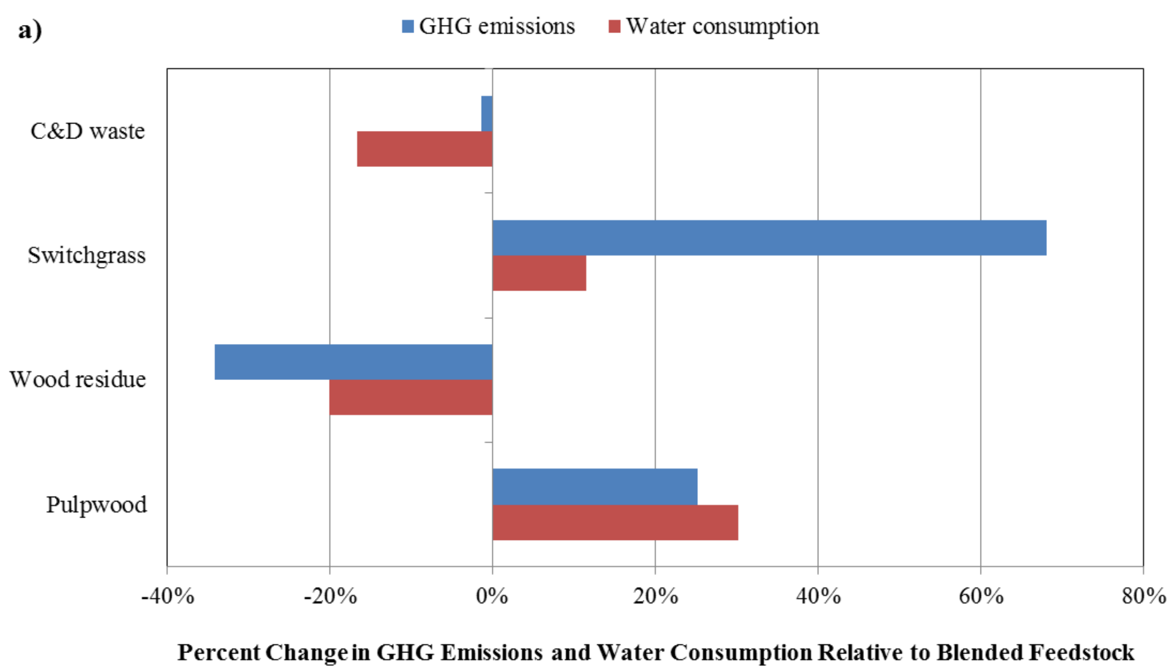
FIGURE 5 Supply chain water consumption of HOG produced via IDL in comparison to water consumption of petroleum gasoline blendstock

3.2 Sensitivity analysis

In Section 2.2, we described how chemicals consumed at low levels that lack publicly available data regarding the material and energy intensity of their production were excluded from the analysis. Together, these inputs constitute 17% (10.1 g/gal) of the mass of process inputs. LO-CAT chemicals make up the largest portion (90%) of this mass. One way to test the sensitivity of results to exclusion of these compounds is to increase the flow of the most GHG-and energy-intensive process input by the total mass of the excluded compounds. We therefore increased the input mass of the beta zeolite catalyst, which has a GHG intensity of 7.2 kg CO_2e/kg, by 10.1 g/gal. As a result, supply chain GHG emissions of HOG increase by 4% to 17 g CO_2e/MJ, which is still an approximately 82% reduction in supply chain GHG emissions as compared to conventional gasoline. Because the bulk of these excluded process inputs are LO-CAT chemicals which contain a significant amount of chelated iron and caustics, it is likely that the GHG intensity of beta zeolite catalysts overestimates the GHG intensity of these compounds. For example, GHG emissions for a representative caustic, sodium hydroxide, are about one-third of those for the beta zeolite catalyst (ANL 2015). Overall, the exclusion of these chemicals is expected to have only a minor influence on the supply chain GHG emissions of the HOG product.

A sensitivity analysis was conducted to examine the effect of the biomass feedstock blend ratio on the supply chain GHG emissions and water consumption, with a focus on extreme scenarios where a single type of biomass feedstock is used for the HOG production via IDL.

Figure 6 (a) shows the effect of using a single type of feedstock for HOG production on the supply chain GHG emissions and water consumption of this fuel, compared to the 2017 design case, which uses a blended feedstock. We found that producing HOG purely from wood residue would have lower GHG emissions and water consumption than when the blended feedstock is used, reducing these metrics by about 34% and 20%, respectively. These reductions come about mostly because fertilizer and irrigation water consumption are reduced for feedstock production. The effect for using solely C&D as the feedstock reduces the GHG emissions marginally because, despite reduced supply chain fertilizer consumption, energy consumption in the landing preprocessing/sorting stage is higher for this feedstock (Table 1) as compared to the blended feedstock. Using C&D waste entirely would reduce water consumption by about 17%, primarily because of reduced fertilizer consumption. On the other hand, if either switchgrass or pulpwood is used as the sole feedstock for HOG production, both GHG emissions and water consumption would increase to varying extents. For example, about 68% and 11% more GHG emissions and water consumption than those for the blended feedstock case are expected when switchgrass is the sole feedstock, compared to about 25% and 30% higher GHG emissions and water consumption when pulpwood is the sole feedstock. The much higher demand for nitrogen fertilizers for production of switchgrass than that for production of pulpwood (Wang et al., 2013) is the main cause of the much higher increase in GHG emissions for using exclusively switchgrass. It is important to note, however, that switchgrass fertilizer requirements are spatially dependent and subject to improvements in switchgrass agricultural practices, which are still emerging. HOG produced from 100% pulpwood has higher water consumption than that from 100% switchgrass mostly because this feedstock is expected to consume more potassium and phosphate fertilizers, the production of which are water-intensive (Lampert et al., 2014; Wang et al., 2013). Again, fertilizer requirements are spatially-dependent and will evolve as production of this feedstock matures. This sensitivity analysis reveals that wood residue is, in the case of this analysis, the most desirable feedstock for both GHG emission reduction and water consumption reduction, as shown in Figure 6 (b). Considerations such as feedstock GHG- and water-intensity may be taken into account in addition to economic factors when selecting a feedstock blend.



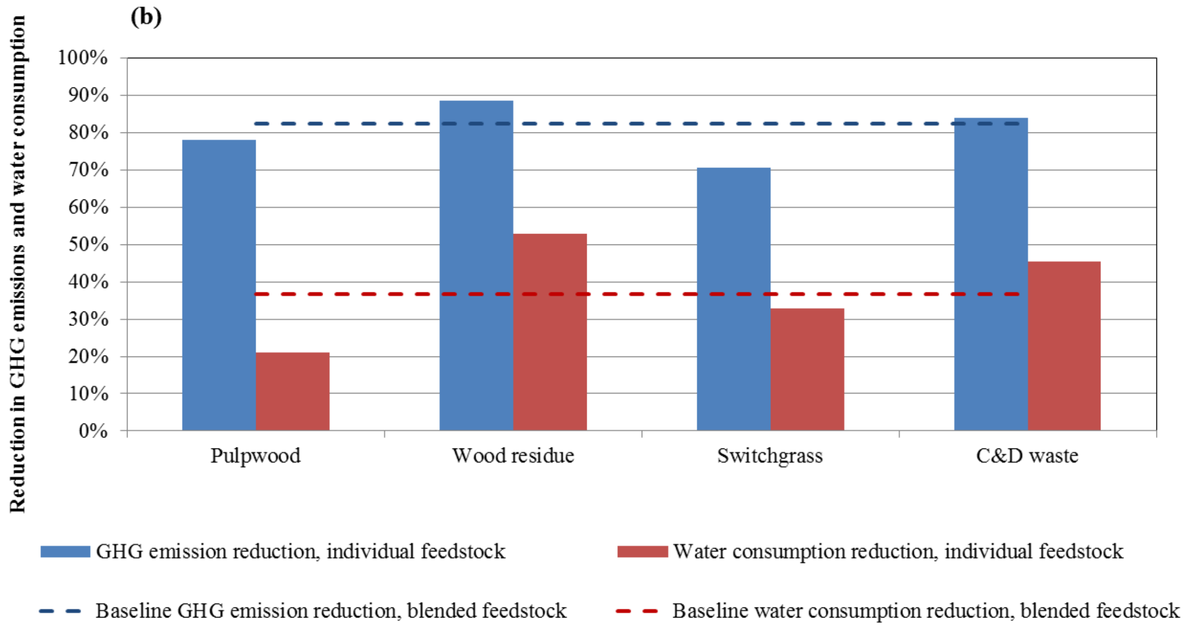


FIGURE 6 Sensitivity analysis of feedstock choices: (a) changes in supply chain GHG emissions and water consumption of HOG produced with individual feedstock, relative to blended feedstock (baseline values: 16.4 g CO_2e/MJ, 0.09 L/MJ); and (b) comparison of blended feedstock and feedstock-specific reductions in supply chain GHG emissions and water consumption of HOG, relative to petroleum gasoline blendstock (baseline values: 93.4 g CO_2e/MJ, 0.14 L/MJ)

Land use change GHG emissions are not included in this analysis. C&D waste and forest residue would likely have little or no LUC associated with them. Direct LUC to production of switchgrass would likely see soil organic carbon (SOC) increases, resulting in some carbon sequestration in soils (Qin et al., 2015). Conversion of lands to produce pulpwood could cause SOC increases, but the influence of LUC on soil carbon stocks is highly dependent on land-use history, local soil and climate conditions, and local feedstock yields.

4 CONCLUSIONS

Producing high-octane gasoline via indirect liquefaction from a biomass feedstock blend consisting of pulpwood, wood residue, switchgrass, and C&D waste yields a fuel that is 82% less GHG-intensive and 37% less water-intensive throughout its supply chain than conventional gasoline. GHG emissions from the feedstock preprocessing were the largest contributor to supply chain GHG emissions among the feedstock logistics steps, while the IDL process itself presents a minor emission source owing to its energy self-sufficient nature. Research and development efforts to further reduce supply chain GHG emissions could focus on reduced consumption of process energy for feedstock preprocessing, minimization of feedstock losses, and boosting of the HOG fuel yield. Although relatively water efficient, the IDL process is the most water-intensive step in the supply chain and represents the largest potential to further reduce water consumption for the pathway. Feedstock loss minimization would lower the water intensity of the HOG fuel. Sensitivity analysis shows that a change in the feedstock blend ratio can significantly change the GHG emissions and water consumption of the HOG via IDL pathway, increasing or decreasing its potential to reduce GHG emissions and water consumption, relative to its petroleum gasoline blendstock counterpart.

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